IV.H.3 Development of a Thermal and Water Management System for PEM Fuel Cells

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Objectives

To assist DOE in developing a humidification and cooling system for proton exchange membrane (PEM) fuel cells in transportation applications

- Study cathode humidification for a pressurized 50 kW fuel cell power system
- Analyze steady-state automotive operation conditions for comparison of concept schematics
- Establish thermal and water management (TWM) system/component specifications
- Demonstrate the performance of a breadboard TWM system with research hardware

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program (HFCIT) Multi-Year Research, Development and Demonstration Plan:

- C. Thermal Management (Transportation system)
- R. Thermal and Water Management (Component)

Approach

- Analyze and compare 4 different cathode humidification systems, down select two systems for further investigation
- Conduct radiator trade study to explore design options for stack waste heat rejection
- Perform detailed system designs and develop component specifications
- Obtain component hardware and conduct component performance testing
- Integrate TWM system and demonstrate performance with a fuel cell simulator

Accomplishments

- Established fuel cell stack and air compressor interface requirements

- Conducted adsorbent wheel and membrane humidifier sub-scale component performance tests
- Evaluated porous plate material basic properties and established an analytical model for component sizing
- Completed cathode humidification concept analysis and down-selected two systems (gas-to-gas humidification) for go-forward detailed designs
- Completed radiator trade study and compared three types of design options
- Held concept design review meeting with DOE and developed a go-forward plan

Future Directions

- Change scope to study 80 kW fuel cell power system, per DOE request
- Complete detailed system designs at DOE specified conditions: dry day, 40°C and 20°C ambient, 80-20-8 kW steady state operations
- Set up test stand
- Obtain component hardware and perform component performance testing
- Integrate TWM system and demonstrate performance

Introduction

This project started in late September 2003. Most of the efforts in 2003 were focusing on programmatic issues. Tasks accomplished including risk mitigation of vender commitment, connection with Argonne National Laboratory for fuel cell characterization, DOE kick-off meeting for determining program scope, Honeywell internal kick-off meeting, connection with fuel cell/ automotive OEMs at the 2003 Fuel Cell Seminar, etc. System concept analysis started in Q4 2003 and continues into 2004.

Approach

A systematic trade study has been completed in selecting the most promising water and thermal management systems from five different concepts using an absorbent wheel, a membrane humidifier, a porous metal foam humidifier, a cathode recycle compressor, and a water injection pump respectively. Selection is done as part of a Quality Function Deployment (QFD) analysis with requirement priority established in the following descending order: size, reliability, cost, power consumption and weight. DOE approved the priority list for the project at this research stage. Two systems (adsorbent wheel and membrane humidifier) using gas-to-gas humidification were selected.

Radiator design trade studies had been performed to examine design options for a 50 kW PEM fuel cell power system. Coolant loop design using an advanced heat exchanger radiator will be conducted along with humidification system detailed design. Honeywell and DOE are working on detailed requirements for a go-forward plan.

At the completion of detailed system design, components will be specified. Component hardware will be acquired in 2005 and will undergo performance tests. System integration will be demonstrated with a PEM fuel cell simulator in 2006.

Results

(1) Air Management Interface

The air management interface system has been established using the development results of a fuel cell turbo-compressor that has been separately funded by DOE. Compressor performance has been studied for compressed air properties that affect the TWM system design. At cold ambient temperature and low power, the compressed air needs to be heated upstream of the humidifier. Potential solutions for this could be using an electric heater or a compressor recycle loop, as shown in Figure 1. A portion of the compressed air is brought back to the inlet of the compressor through a flow control valve and a closed temperature control loop consisting of a

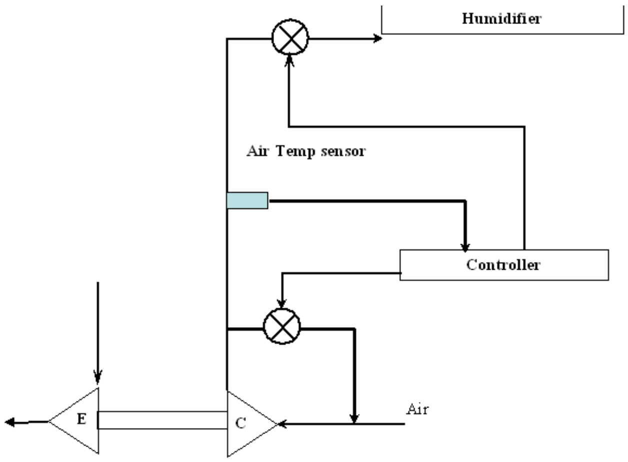

Figure 1. Compressor Recycle for Air Heating

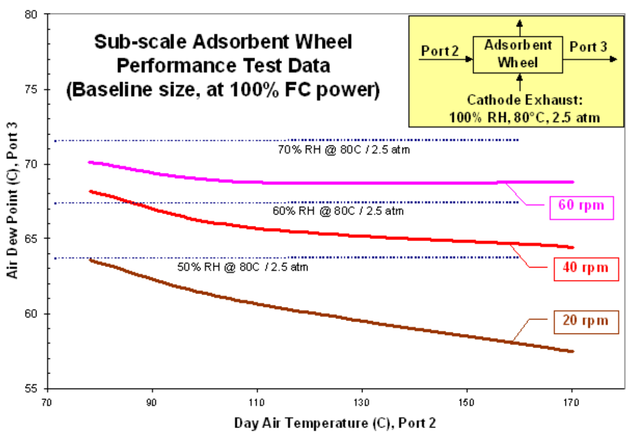

Figure 2. Adsorbent Wheel Performance

temperature sensor and a controller. Detailed system study of cold operation is not covered in this project.

(2) Adsorbent Wheel

A full-scale design for 50 kW PEM fuel cell applicationshas been completed. The wheel humidifier is 6” long with a 5.6” internal diameter. It is made of cordierite, 400 cells per inch, 6.5 mils wall thickness, and coated with Alumina desiccant. Because of the compressor capacity limitation at the vender’s facility, 80% of the wheel surface is radial blocked during performance testing. With 20% opening surface, simulating a 10kW fuel cell flow rate, performance testing is completed at 100%, 50%, and 25% power levels. Figure 2 shows a typical performance chart at 100% power flow rate.

Honeywell developed an analytical adsorbent wheel model and is using it in system analysis. Concept system modeling and sizing are completed. Preliminary sizing of the adsorbent wheel humidification system is shown in Table 1 based on simulation results.

Table 1. Adsorbent Wheel Humidification System Parameters

	Wheel
Size, cu.ft.	0.28
Reliability, hr	30,000
Cost, sale price	$310
Power, kW	0.03
Weight, lb	16

(3) Membrane Humidifier

A commercially available membrane humidifier having an active surface area of ~196 in^2 was used for performance tests. This unit is about 1/14 of the full-scale device that can handle 50 kW fuel cell flow rate. Again, the reason for testing a sub-scale unit is the vender's facility limitation. Sub-scale unit performance tests are completed at 100% and 25% power levels. A typical performance chart is shown in Figure 3.

Empirical testing for analytical model validation is completed. The preliminary system sizing is shown in Table 2.

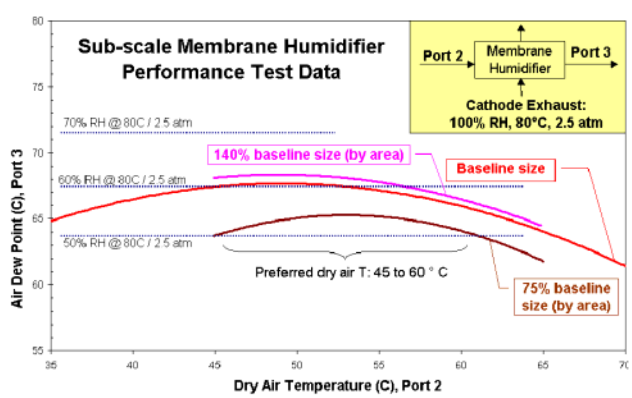

Figure 3. Membrane Humidifier Performance

Table 2 Membrane Humidifier Humidification System Parameters

	Precooler	Precooler Fan	Membrane	Water Trap	Total
Size, ft^3	0.118	0.111	0.141	0.029	0.399
Reliability, hr	200,000	170,000	250,000	150,000	46,406
Cost, sale price*			$250		
Power, kW	0	0.72	0	0	0.72
Weight, lb	4.79	1.16	2.75	0.5	9.20
* Note: sale price is based on 100,000 units/year					

(4) Porous Metal Foam Humidifier

Evaluation tasks started in late March and are in progress. The vender designed and fabricated samples with various manufacturing processes to determine the optimum material property for his humidification application. Material permeability and bubble pressure are tested. The metal used is FeCrAlY alloy, 70% Fe, 25% Cr, 5% Al, with a trace of (~.1%) Y. Options for improving material performance have been considered and tested in May.

Theoretical analysis of this porous humidifier is based on the material property data and certain heat and water transport equations. System analysis and sizing are completed. The preliminary porous plate humidification system sizing is shown in Table 3.

Table 3 Porous Plate Humidifier Humidification System Parameters

	Precooler	Additional Precooling*	Fan	Porous Plate	Total
Size, ft^3	0.0622	1.875	0.111	0.099	2.147
Reliability, hr	200,000	90,000	170,000	150,000	34,892
Power, kW	0	1.2	0.14	0	1.34
Weight, lb	6.2	2.0	5.56	7.5	39.26
* Reliability to be nominally representative of a refrigerant evaporator and controls, added to the vehicle VCS utility.					

(5) Cathode Exhaust Recycle

Analysis is complete. Findings are:

- To reach 60% relative humidity (RH) air humidification at the cathode inlet, water spray is required. A water separator, a condenser, a water tank, and a water pump are needed.
- A pre-cooler is required to remove heat from the compressed air during hot days and high power operations.
- A recycle fan is less attractive than a recycle compressor because of higher power consumption.

A cathode recycle compressor alone is insufficient for fuel cell humidification. Water injection is required to make up the additional water vapor. Considering system configuration complexity, the cathode recycle compressor concept does not offer an advantage over the system using water injection only. Water injection humidification is analyzed and presented in the next paragraph.

(6) Water Injection Humidification System

The analysis results show that a pre-cooler for compressed air is not needed because of cooling from water evaporation latent heat. This system can hit 50% and 90% RH but with low cathode inlet temperatures. System sizing is presented in Table 4.

Table 4 Water Injection Humidification System Parameters

	Water Trap	Condenser	Fan	Water Pump	Total
Size, ft^3	0.029	0.090	0.0953	0.002	0.216
Reliability, hr	150,000	300,000	50,000	45,000	19,149
Power, kW	0	0	1.59	0.057	1.65
Weight, lb	0.5	25	8.56	0.75	34.81

(7) System Down-select

Quality Function Deployment analysis is used to compare and evaluate four different humidification systems described above. Data and results are presented in Tables 5-1 and 5-2. The membrane humidifier and adsorbent wheel humidification systems are the two best options with current priority and weight factor settings.

Table 5-1 QFD Raw Data

Priority Metric Units	**5** Volume ft3	**4** Failure Rate failures/ (million hr)	**3** Cost Relative Rank	**2** Power kW	**1** Weight lb
Baseline	0.22	52.2	1	1.65	34.8
Plate	2.15	28.7	2	1.34	39.3
Membrane	**0.40**	**21.5**	**2**	**0.72**	**9.2**
Wheel	**0.28**	**33.30**	**2**	**0.03**	**16.0**
Raw Sum, Σ^x	**3.04**	**135.8**	**7**	**3.74**	**99.3**

(8) Radiator Thermal Performance Trade Study

Radiator design trade studies have been conducted. Three options that have been evaluated are:

- Conventional “automotive” type plate-fin design,
- Conventional “aerospace” type plate-fin design,
- Advanced microchannel type plate-fin design.

The purpose of this study has two objectives, (1) evaluate radiator size/weight vs. system power consumption and (2) explore design options. Radiator thermal performance analysis is performed at three different power consumption levels with the problem statement stated in Table 6. Study results indicated that Honeywell automotive radiator design should be used as a design backbone and can be improved with aerospace & micro-channel technologies.

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Table 5-2.QFD Normalized Data

Normalization	**(Σx - x)Σx** between 0 (worst) and 1 (best)					**Weighted Sum:**
Weight factor:	**5**	**4**	**3**	**2**	**1**	
Baseline	0.929	0.615	0.857	0.559	0.649	11.4
Plate	0.294	0.789	0.714	0.641	0.605	8.7
Membrane	**0.869**	**0.841**	**0.714**	**0.807**	**0.907**	**12.14**
Wheel	**0.908**	**0.754**	**0.714**	**0.992**	**0.839**	**12.5**

Table 6. Thermal Performance Analysis Problem Statement

Heat rejection rate = 55kW			
Hot Flow:	Glycol/Water (50/50)		
Flow Rate:	40	gpm	
Tin:	147	^{o}F	(75 ^{o}C)
Pin:	50.3	psia	
Cold Flow:	Air		
T_in_air:	104	^{o}F	(40^{o}C)
P_in_air:	14.7	psia	

Conclusions

- Two cathode humidification systems (adsorbent wheel and membrane humidifier) will be further analyzed in system detailed design.
- Honeywell automotive radiator design should be used as a design backbone and can be improved with aerospace & microchannel technologies.
- Development opportunities identified:
  - Product development of adsorbent wheel – focus on reliability, sealing, size, and weight.
  - Lower cost and higher temperature resistance material for membrane humidifier.

FY 2004 Publications/Presentations

1. “Development of Thermal and Water Management (TWM) System for PEM Fuel Cells,” by Chung Liu, DOE Stationary & Transportation Fuel Cell Project Kick-off &

Coordination Meeting, February 17, 2004; Washington DC

2. "Air, Water and Thermal Management for PEM Fuel Cell Systems," Abstract submitted to 2004 Fuel Seminar (Mark Gee and Chung Liu).

3. “Development of Thermal and Water Management (TWM) System for PEM Fuel Cells,” by Chung Liu, 2004 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review Meeting, May 26, 2004; Philadelphia, PA

Special Recognitions & Awards/Patents Issued

1. A patent disclosure of "Approaches of solving humidification device turndown ratio for PEM fuel cells" has been submitted to Honeywell internal council for review.